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Dynamic Pressure Testing of a 155-mm Howitzer Ballistic Window Using a Closed Bomb Vessel

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14. ABSTRACT

The U.S. Army Research Laboratory (ARL) was tasked by the Armament Research, Development and Engineering Center (ARDEC) to dynamically pressure test a chamber window design that is required to withstand dynamic loads up to 63.3 ksi. The window is a part of a proposed system to replace the chemical primer with a Diode Pumped Laser Ignition System (DPLIS) for use on the M777 LW155 towed howitzer. A modified closed bomb vessel, manufactured by Harwood Engineering and initially designed for propellant characterization, is used to simulate a launch environment and place the window under the requisite dynamic loading. The propellant used for testing was MACS M232A1. While the closed bomb is primarily used for obtaining propellant burning rates, this report is intended to illustrate the versatility of the closed bomb for use in nonconventional testing.

15. SUBJECT TERMS

Closed Bomb, Ballistic Window, Laser Ignition, Pressure Test

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1. Introduction

Closed bomb vessels have been incorporated for many years, primarily to characterize the linear burning rate of propellants (*1*). However, being a high-pressure test vessel, such vessels can also be used to simulate the pressures experienced in a gun barrel while accurately measuring the pressure within the vessel. The main components of the closed bomb are the thick-walled steel vessel, which contains the event; the propellant to produce the pressure; a squib, which consists of an electric match and a small quantity of black powder to ignite the propellant; a pressure gauge to measure the chamber pressure in the vessel, and a data acquisition system to record the data.

Since the closed bomb is nothing more than a high-pressure vessel, it can be modified for a variety of uses. One such use, which was tasked to the U.S. Army Research Laboratory (ARL) by the Armament Research, Development and Engineering Center (ARDEC), was to prove the survivability of ballistic window designs intended for use in laser ignition. The purpose of the window is to replace the chemical primer system on a M777 LW155 towed howitzer with a laser ignition system; therefore, the window is required to survive a high-pressure environment. In order to accomplish this, we performed slight modifications on an existing closed bomb in inventory such that it would accept the window housing. We then incorporated the M232A1 MACS propellant in order to generate the requisite pressures in the bomb.

2. Background

The chamber window being tested is used to protect and provide an optical path for the laser head of the Diode Pumped Laser Ignition System (DPLIS), which is a proposed replacement for chemical primers on the M777 LW155 towed howitzer. The original chamber window, developed under the Crusader and Future Combat Systems programs, was structurally robust but required a specialized cleaning system, which is unavailable on the towed platform.

Improved windows were designed in conjunction with finite element analysis software in an effort to improve ease of cleaning by the gun crew. For economical purposes, closed bomb pressure testing was performed to simulate the live-fire environment of the gun chamber and determine the new windows' survivability. This included using a closed bomb apparatus and a hydraulic drop hammer to generate appropriate pressure-time profiles. A number of designs have been proposed and tested with varying degrees of success.

The window needed to meet a requirement of surviving pressures up to 63.3 ksi for 55 shot cycles in order to be qualified. Meeting this test qualification would make the window's design acceptable to go forward with gun testing where maximum pressures seen are 61.3 ksi.

Testing of optical, ballistic windows is not a particularly novel idea; however, previous tests used a different apparatus (*2*). The main difference between past and present testing is that the previous test apparatus was designed with a controlled leak to ensure the window experiences peak pressure for only tens of milliseconds. Previous conclusions indicate a critical characteristic of ballistic window design is how they are assembled and seated into their housing.

3. Equipment Setup

The equipment used for testing consisted of a Harwood Engineering double-ended closed bomb vessel (figure 1), a Kistler Type 607C high pressure sensor, a Kistler model 5100B1 dual-mode charge amplifier, fffg black powder, electric matches, M232A1 MACS propellant, and the XLCB data acquisition and reduction program (*3*, *4*). However, in this experiment the only function of the XLCB program was to record a pressure-time history for each shot. Propellant properties and characterizations were irrelevant for this set of experiments.

This particular experiment was unique in the fact that a double-ended bomb was needed in place of the standard 200-cc bomb. The primary differences between the two apparatuses is that the 200-cc bomb has a closure plug on one end to accommodate the firing mechanism and a venting valve on the other end of the bomb, while the double-ended bomb has a closure plug on each end and is vented through the center portion of the vessel body. The double-ended vessel was necessary in order to exploit one of the chamber closures to accommodate the test window, as shown in figure 2. The other chamber closure would be used in its standard fashion as the location of the ignition source.

The double-ended bomb had a chamber volume of ~465 cc and closure components identical to the Harwood 200-cc closed bomb, which is widely used for standard propellant testing (*5*). Because the chamber volume was much larger than needed, we designed and implemented a modified face plate/steel plug (figure 3) in order to take up volume inside the bomb, thus reducing its effective volume. This modification reduced the amount of propellant needed to reach desired pressures, and in turn, reduced the amount of stored energy in the closed bomb, therefore reducing associated safety risks. The appendix provides detailed drawings of the closed bomb modification needed in order to satisfy the testing requirements.

Figure 1. Double-ended closed bomb apparatus.

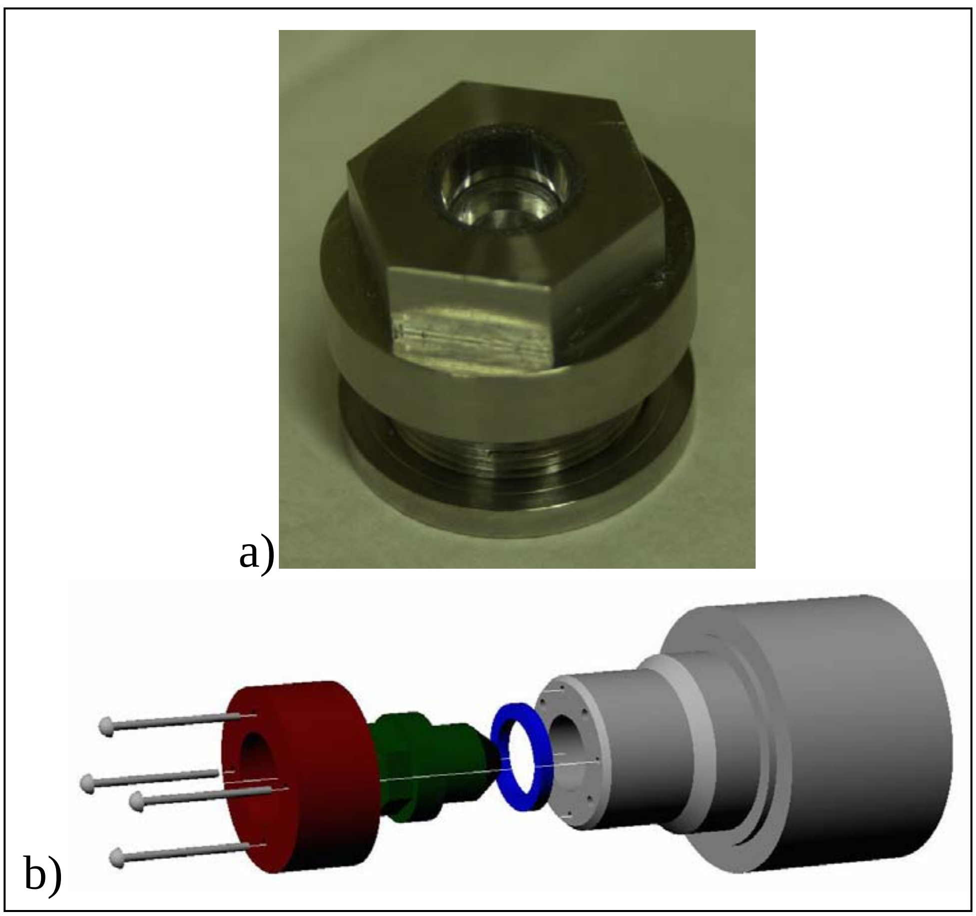


Figure 2. (a) Test window and (b) exploded view of chamber head and window.

Figure 3. Modified closure cap/steel slug insert for closed bomb volume reduction.

4. Calculating Charge Weights and Volume

The primary function of the closed bomb vessel is to characterize propellants. Knowing the chamber volume as well as the propellant's mechanical and thermochemical properties, one can calculate a burning rate using the empirically measured pressure-time history of the propellant (*6*). In this study, burning rates were of no interest; however, we wanted to calculate the chamber volume in order to determine the appropriate charge weights needed to achieve the desired chamber pressure.

Without first knowing the closed bomb volume, the most direct way to calculate the amount of propellant needed to provide a desired pressure is to fire a few shots in the closed bomb at varying charge weights and calculate the linear relationship of charge weight to pressure. This method of determining appropriate charge weights is possible given that the governing equation of state for the closed bomb is

$$PV_s = \frac{m_p R_s T}{MW}, \tag{1}$$

where P is pressure, V_s is system volume, m_p is propellant mass, R_s is the system's gas constant, T is the adiabatic flame temperature of the propellant, and MW is the molecular weight of the propellant. Here it can be seen that P is linearly proportional to m_p, which is just a function of propellant mass; while volume, gas constant, temperature, and molecular weight are all constants. When employing this method, precaution must be taken to assure one does not over-

pressurize the bomb; therefore, a low loading density should be chosen for an estimated bomb volume. So while the bomb volume is still unknown, its value is not necessary in calculating appropriate charge weights for a given propellant. The charge weights necessary to achieve desired pressures for this test were derived from the empirical calibration firings at various loading densities and incorporation of equation 1. From this linear fit, a loading charge to pressure relationship can then be used for the duration of the test (i.e., 93.6 g propellant for 60 ksi).

For future tests, it is best to know the volume of the bomb so one can accurately predict pressures, as opposed to engaging in the cumbersome method of firing calibration shots, which takes substantial time and effort. We can take equation 1 and substitute

$$\frac{R_s T}{MW} = I \,, \tag{2}$$

where I is then defined as the impetus of the propellant, which is generally a known thermochemical property. From this, we now have a given I and a known P and m_p from empirical firings, and thus can calculate V. Through these calculations, we determined the effective chamber volume (with steel plug) of our bomb to be 235 cc.

5. Test

Over the course of the test, ARDEC provided ARL with various window designs for testing. In total, nine different designs were put into the closed bomb and tested, one of which was a control window that is known to be able to survive the intended environment. However, this window was unusable for application purposes due to the difficult nature of cleaning it.

Initially, each window was put through a seating procedure before undergoing the full up pressure shots. The seating procedure consisted of firing nine shots at progressively higher pressures: three shots at a low pressure (10 ksi), three shots at a medium pressure (35 ksi), and three shots at a high or full up pressure (55 ksi). During the evolution of the test, this 55 ksi upper limit was eventually pushed to 60 ksi and ultimately 63.3 ksi. After the window was seated, it underwent 55 additional shots at full pressure in order to be deemed gun usable. In an effort to save time, the windows were inspected after every third shot to check for compromises in integrity.

Aside from the window's presence in the pressure vessel, the operation of the closed bomb was identical to any regular propellant characterization test. That is to say, the bomb was cleaned, loaded, and fired in the same manner and no special precautions or procedures were necessary during testing.

During testing none of the window designs were able to survive the high-pressure conditions present in the closed bomb. They all showed some manner of fracture, either internal to the sapphire crystal or on its surface, as illustrated by figure 4. Table 1 shows a shot by shot test summary for the windows. The nomenclature used for the windows was an internal method of accounting for design differences. After several window designs failed, window 1005 was incorporated into the test matrix as a control window. This window is known to be able to survive the launch dynamics of a gun, and if it failed in the closed bomb, then it would indicate that the bomb was not accurately replicating the gun conditions and could not be used as a reliable indicator of window survivability. Unfortunately, during the testing of window 1005, there was a mechanical failure in the closed bomb. Figure 5a shows how the vent valve catastrophically failed and was launched from the bomb body while the closed bomb was pressurized. The failure is likely a result of the valve not being adequately secured to the bomb, which resulted in a much larger valve surface area for the bomb pressure to interact with, thus causing the threads to fail. As a precaution, the vessel was sent back to the manufacturer for quality inspection and was returned after no defects were detected. The test was subsequently continued with more window designs, which also failed.

The test was ultimately ceased due to a mechanical failure of the closed bomb that rendered it unusable. The valve seat on the closed bomb had eroded in such a manner that a proper seal between the bomb and valve could not be obtained. This was ultimately discovered upon closer inspection of the seating area following consecutive valve failures. Figure 5b shows the elongation of the eroded area of the bomb’s valve seat, and the valve stem showing evidence of gas erosion from the high-pressure leak around the seating area. Unfortunately, the history of this vessel was unknown and no record of usage was available so the failure could not have been foreseen.

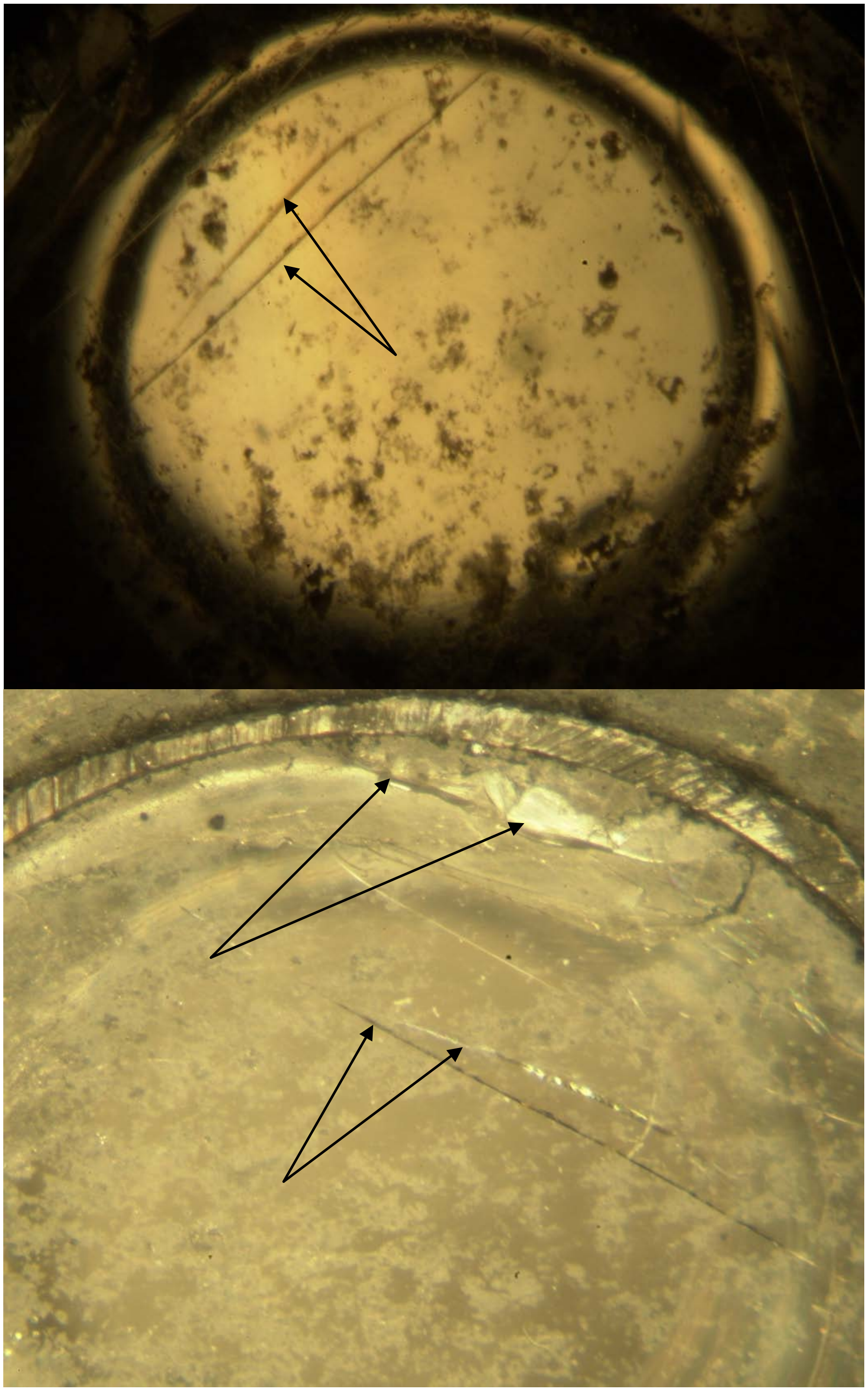


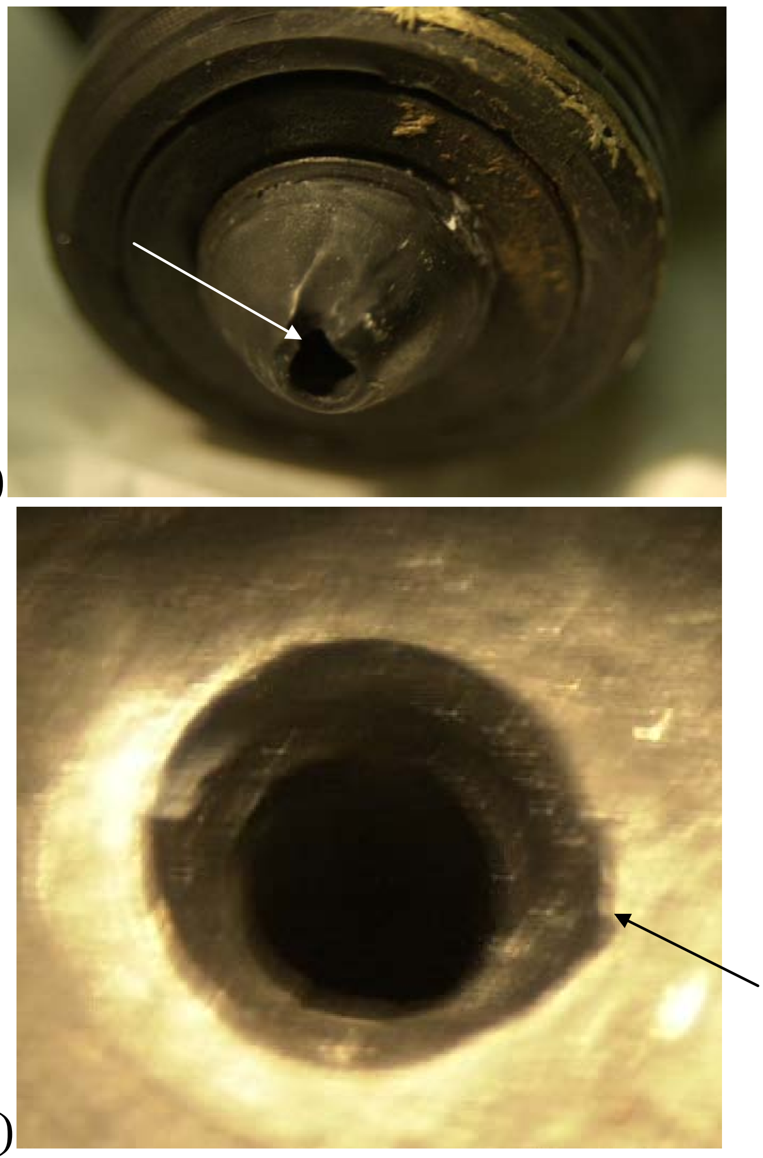
Figure 4. Failures of the window.

Table 1. Peak pressure data.

Detailed Pressure Data				
Shot	Window	Target Pressure (ksi)	Measured Pressure (ksi)	Comments
1	T2	10	NA	
2	T2	10	10.5	
3	T2	10	10.5	
4	T2	35	34.8	
5	T2	35	35.4	
6	T2	35	35.5	
7	T2	55	NA	
8	T2	55	56.4	
9	T2	55	56.1	
10	N1	10	11.5	
11	N1	10	10.7	
12	N1	10	11.2	
13	N1	35	34.5	
14	N1	35	35.7	
15	N1	35	NA	
16	N1	55	55.1	Window cracked
17	T2	55	54.1	
18	T2	55	53.5	
19	T2	55	55.3	
20	T2	55	55.5	Window cracked
21	T1	10	14.3	
22	T1	10	10.6	
23	T1	10	10	
24	T1	35	34.8	
25	T1	35	35.5	
26	T1	35	35.5	
27	T1	55	53.7	Window cracked
28	1005	10	NA	
29	1005	35	35.4	
30	1005	60	59.3	
31	1005	63	60.9	Valve assembly broke
32	22	35	30.7	
33	22	60	NA	
34	22	60	NA	
35	22	60	50.7	
36	22	60	56.2	
37	TRA-06	35	NA	
38	TRA-06	60	46	New pressure gage incorporated
39	TRA-06	60	47.4	Window cracked
40	BA1	35	26.3	
41	BA1	60	NA	
42	BA1	60	43.5	Window cracked
43	TRA-03	35	26.7	
44	TRA-03	60	43.2	Window cracked

Table 1. Peak pressure data (continued).

Detailed Pressure Data				
Shot	**Window**	**Target Pressure (ksi)**	**Measured Pressure (ksi)**	**Comments**
45	None	60	NA	
46	None	60	42.5	
47	None	60	NA	
48	None	60	NA	Valve assembly broke
49	None	35	29	Valve assembly broke



a) b)

Figure 5. Vent valve failure, showing a) erosion around vent valve and b) erosion and elongation of closed bomb valve seat.

6. Results

We recorded pressure-time curves from the shots performed as well as the peak pressure values (figure 6). All the pressure-time curves behaved as the one illustrated in figure 6; therefore, only one pressure-time curve is included for representative purposes. The blue line represents the raw recorded data, the pink line is the reduced data, and the green line represents the change in pressure of the reduced data. Table 1 shows a recapitulation of the data recorded, along with the repeatability in obtaining pressures. From table 1, we notice that beginning with the TRA-06 window design, the measured pressure data were substantially lower than the target value, along with the fact that capturing the data became more sporadic. While the reason for failing to capture those event's data is not completely known, it is possible that the low-pressure readings contributed to this inability to capture data. The data acquisition system is triggered by the generation of system pressure, and if the actual pressure is substantially lower than the expected pressure then the system may never have reached the trigger threshold.

The lower recorded pressure values can be attributed to a pressure gauge change during the course of testing. The initial gauge became unreliable during testing so we decided to use another gauge. At this time, the lower pressure readings appeared and prompted an inquiry into which gauge was within calibration and which one was not. In theory, this does not negatively affect the data recorded because the gauge calibration values can be updated at a later time into XLCB and the program can be rerun to return a more accurate data set. After the gauges returned from calibration, we discovered that the original gauge had deviated 25% from its previous calibration, while the second gauge had only deviated 1%. Given this fact, we determined that none of the data recorded with the original gauge were reliable with such a large deviation in calibration; therefore, we did not perform a recalculation of the pressure values.

While not having accurately measured pressure for the majority of the shots is less than ideal, practical conclusions can still be made from the data set available. The shots performed with the second gauge have been validated with the post-test gauge calibration. Because the bomb is a fixed volume and a fixed amount of propellant was incorporated to reach targeted pressures, we can deduce that shots performed with the original, unacceptable gauge produced pressures similar to that of the later shots, which incorporated the second gauge. This information should give solace to all interested parties that the windows were not being over-pressurized and, in fact, were likely failing under pressures much lower than acceptable values.

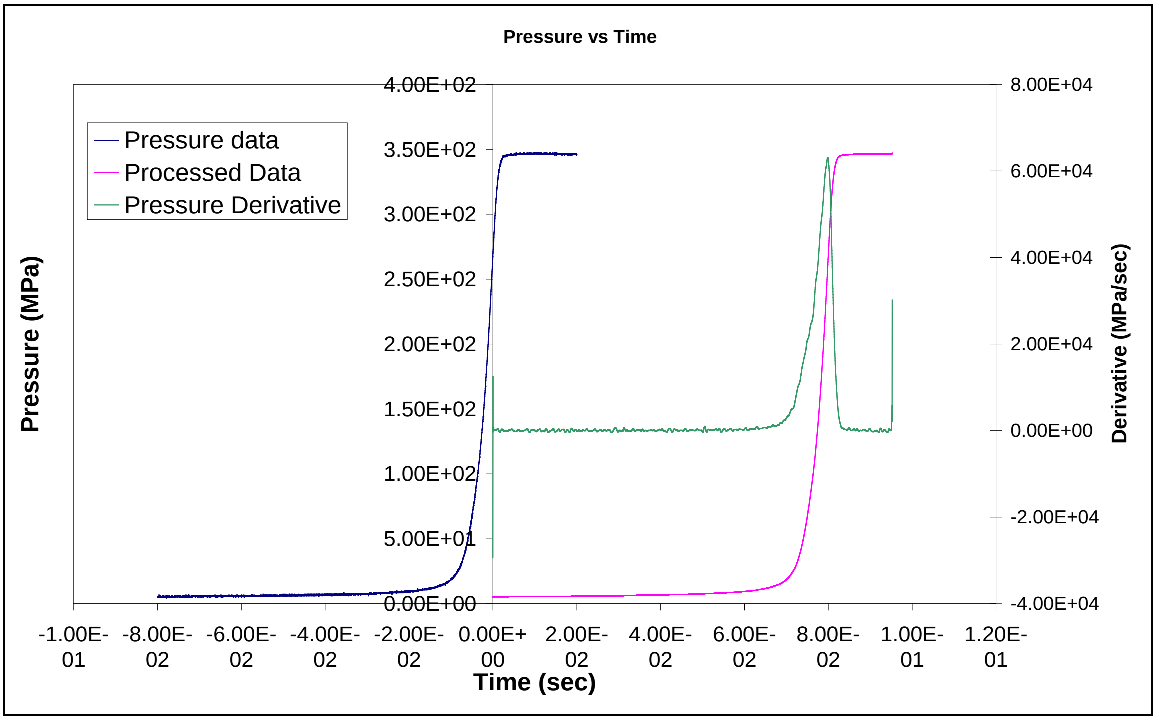


Figure 6. Pressure-time trace of closed bomb event.

7. Conclusions

The double-ended closed bomb was modified to accept a window housing in order to test the window's survivability in a simulated gun environment around 60 ksi. The variety of window designs tested did not survive the closed bomb environment. One possible cause for the failures was a flawed window design. A second possible cause was an unforeseen difference in pressure and thermal environments between a live-fire gun chamber and the closed bomb chamber. The main difference between the two is that gun pressures decay quickly, on the order of milliseconds, as the projectile moves down the barrel, whereas the closed bomb retains the high pressure for a much longer period of time, generally 30–60 s, before venting. Furthermore, the pressure dynamics in a closed bomb may not accurately simulate that of a gun chamber, where unknown pressure waves may be adversely affecting the window.

A third possible failure mechanism of the windows could have been a result of over-pressurizing the closed bomb. This possibility arose when we experienced a discrepancy in the pressure recordings when different gauges were used. However, over-pressurization seems unlikely due to the fact that post-test gauge calibrations showed the secondary gauge to be within specifications and during testing it only recorded values in the 45 ksi range.

While the closed bomb is a useful apparatus that can be modified for operations other than propellant characterization, it is not a be-all, end-all tool for material survivability testing due to the potential differences in the high-pressure closed bomb environment when compared to the environment it is intended to replicate.

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Appendix. Modified Closed Bomb Drawings

Figures A-1 through A-3 display the diagrams for the modifications made to the closed bomb for our experiment.

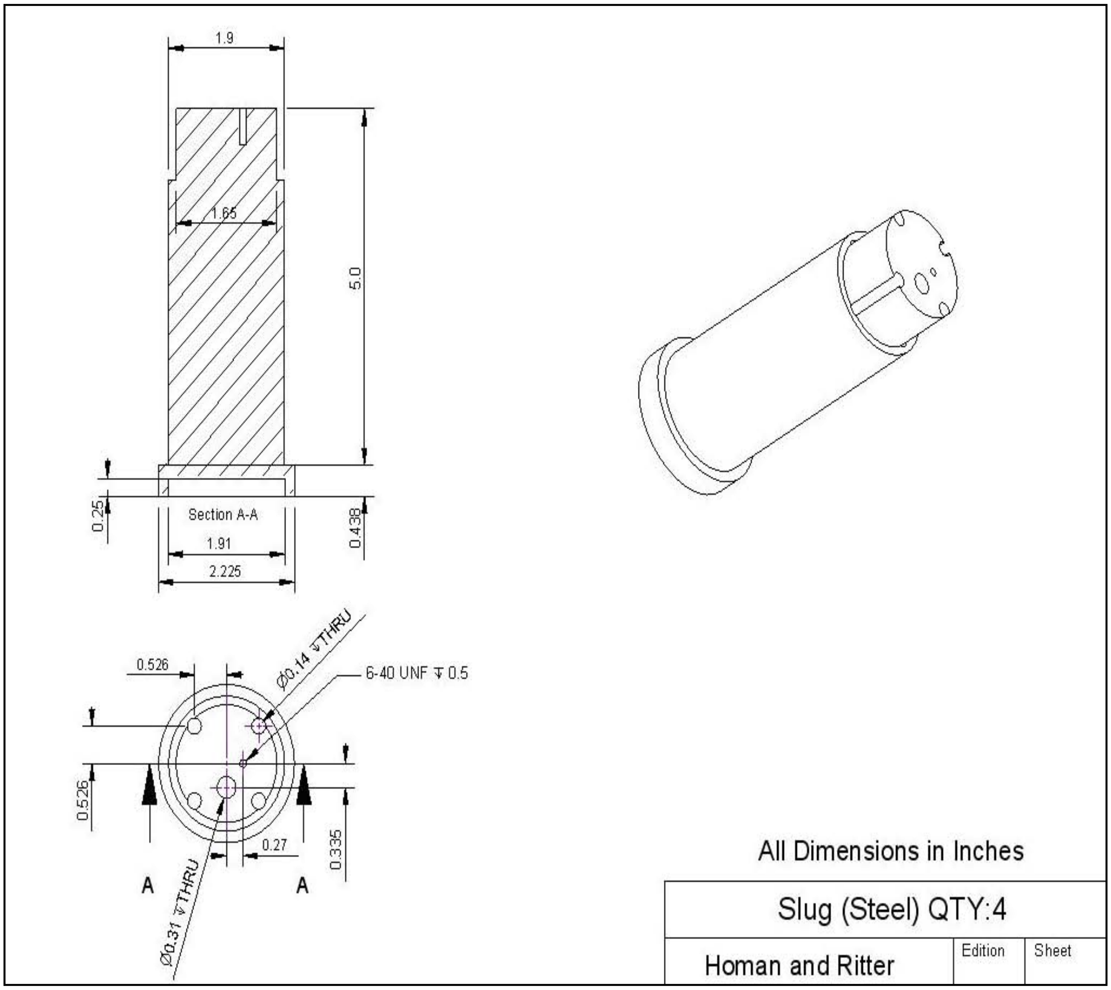

Figure A-1. The steel slug insert.

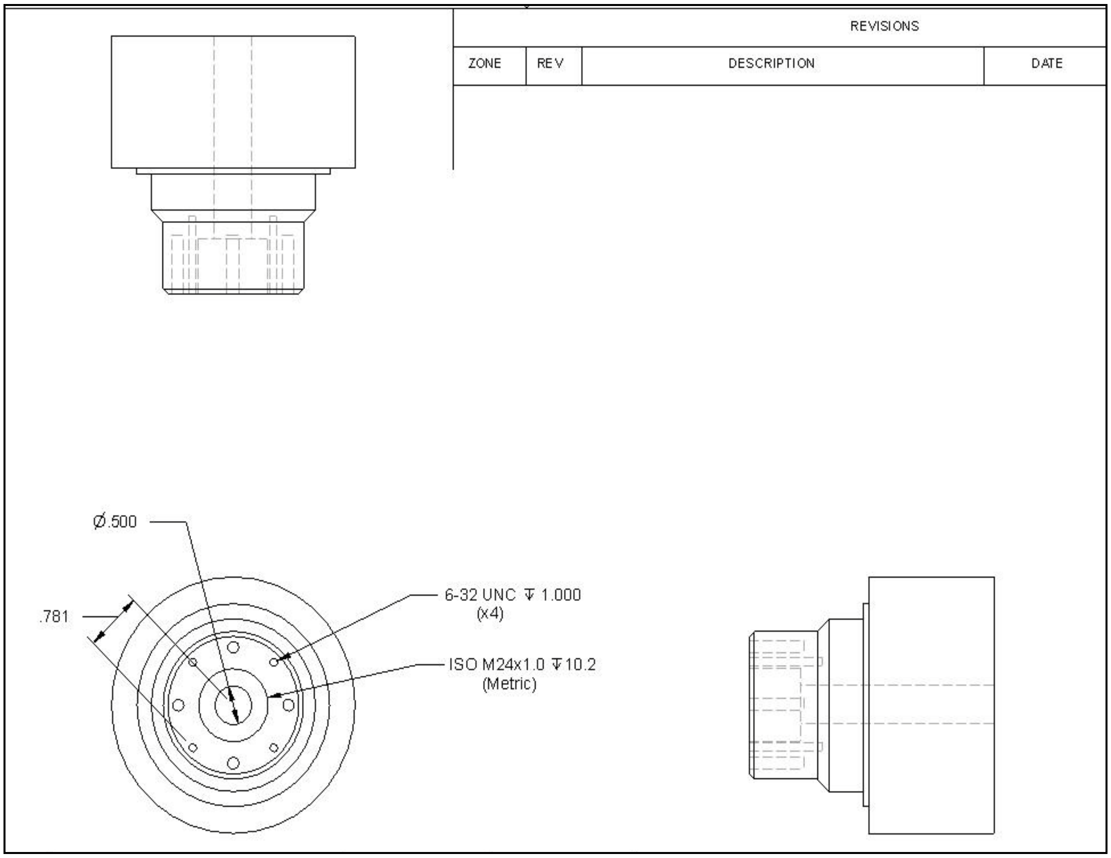

Figure A-2. The modified closure (head).

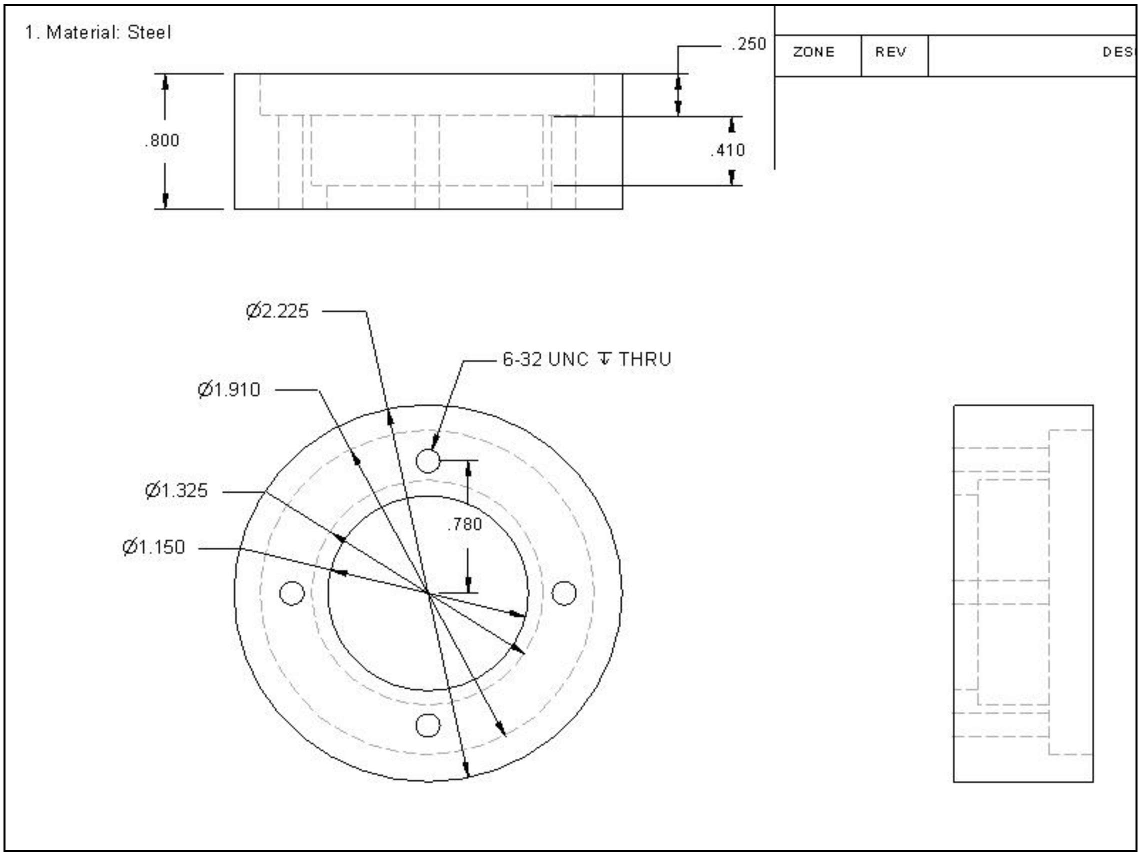

Figure A-3. The modified face plate for closure.

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